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Modeling Gas Dynamics in California Sea Lions

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Award Number: N00014-15-1-2221

LONG-TERM GOALS

The objective of this study is to update a current gas dynamics model with recently acquired data for respiratory compliance (P-V), and body compartment size estimates in California sea lions. The model will be calibrated against measured arterial and venous PO2 levels from California sea lions, and estimate the error between predicted and observed values. The model will be used to investigate specific scenarios where marine mammals could be particularly prone to decompression sickness (DCS) due to changes in dive behavior or physiology.

OBJECTIVES

This project is separated into two aims:

Aim 1: Revise the existing model with new species-specific parameter estimates for California sea lions.

Aim 2: Compare estimated and measured arterial and venous P_{O_2} for diving California sea lions.

APPROACH

This project is separated into two aims: Aim 1) Revise the existing model with new species-specific parameter estimates for California sea lions, which was tested in this fiscal year; Aim 2) Compare estimated and measured arterial and venous P_{O_2} for diving California sea lions.

Aim 1: Pressure-volume (compliance) loops from excised California sea lions lungs and upper airways (trachea) were used to update the parameters that estimate the pulmonary shunt during diving. The compliance estimates were related to lung and tracheal volumes during compression to pulmonary shunt (Bostrom, Fahlman et al. 2008). In the existing model, the compliance parameter for the lung was for inflation. As there is considerable hysteresis in the inflation and deflation limb of the compliance curves, we compared model estimates from both curves. In addition, the existing model's compliance estimate for upper airways was from a terrestrial mammal, whereas we can now use data for California sea lions. Consequently, the pulmonary shunt equations, which are an integral component to estimate gas dynamics during diving, will be revised with species-specific parameters

for the upper and lower airways. This provides a better estimate of how blood and tissue gases are managed during diving and improve our understanding of the links between behavior, physiology and the risk of bubbles during decompression (Hooker et al., 2009; Kvadsheim et al., 2012).

As data for compartment sizes become available for California sea lions, we will update the model with values for each compartment. In addition, the model will be revised to include the species-specific relationship between P_{O_2} and O_2 affinity (O_2 dissociation curve) and Bohr effect, both of which affect available O_2 for tissue specific O_2 consumption.

Aim 2: Dive data, and concurrent venous and arterial PO2 measurements, for California sea lions were requested from Drs. Paul Ponganis and Gitte McDonald and are currently being used to compare estimated and observed blood PO2 levels during diving. A sensitivity analysis will be performed to assess the new and current parameter estimates and error of the model output. If time permits, we will also test the hypothesis that peripheral a-v shunt is a trait that explains the measured arterial and venous PO2 profiles, as previously suggested (McDonald and Ponganis, 2013).

WORK COMPLETED

Aim 1:

Compliance parameters

<u>Updating Alveolar Compliance Estimates</u>

Recently published transpulmonary pressure-volume data collected from 3 California sea lions (Fahlman et al., 2014) was fit to the following alveolar compliance equation:

$$V_{A,N} = a(1 + e^{-c(-b-P_{A,S})})^{-1} \tag{1}$$

where a, b, c, are fitting parameters, $P_{A,S}$ is the structural pressure of alveoli and $V_{A,N}$ is the normalized alveolar volume ($V_A \cdot TAC^{-1}$; Bostrom et al., 2008). Parameters were estimated using a nonlinear mixed effects model, grouping data by individual, where a was a fixed factor and b and c were random factors. Using this model, the best estimates for the alveolar compliance parameters were 1.0347, 1.7638, and 1.8001, compared to the previously-used estimates of 1.1063, 1.2304, and 1.3361 (Fig. 1).

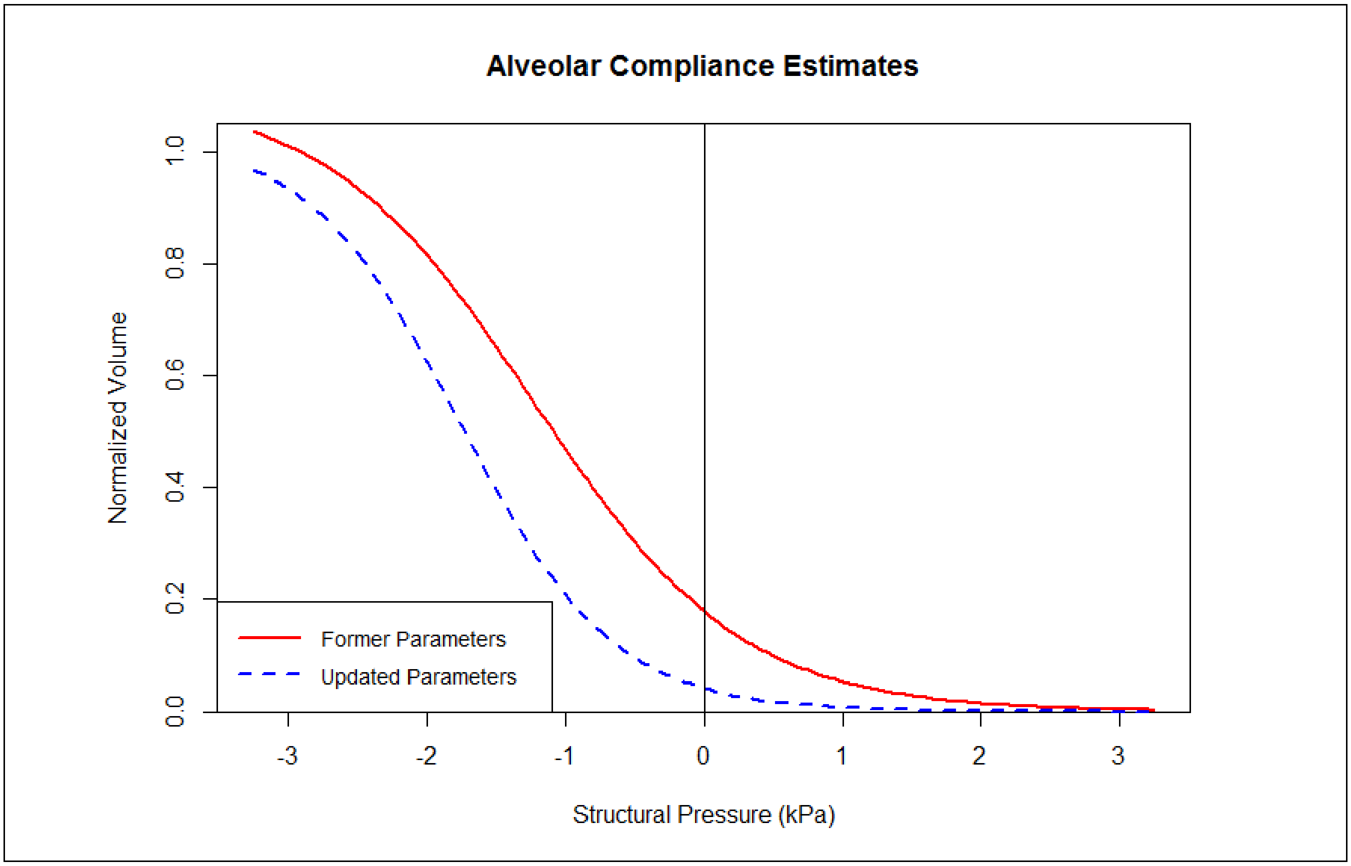

Figure 1. Normalized alveolar volume estimates using the former parameter estimates (red) and the updated parameter estimates (blue).

<u>Updating Tracheal Compliance Estimates</u>

Recently collected tracheal pressure-volume data collected from 3 California sea lions (Moore et al., 2014) was fit to the following tracheal compliance equation:

$$V_{D,N} = (1 - P_{D,S}(0.0981Kp)^{-1})^{-1/n} \tag{2}$$

where Kp and n are fitting parameters, $P_{D,S}$ is the structural pressure of dead space and $V_{D,N}$ is the normalized dead space volume ($V_D \cdot V_{D,o}^{-1}$; Bostrom et al., 2008). Parameters were estimated using a nonlinear least squares model, grouping data by individual, where Kp and n were fixed factors. Using this model, the best estimates for the tracheal compliance parameters were -12.54 and 4.24, compared to the previously-used estimates of -12.78 and 0.907 (Fig. 2).

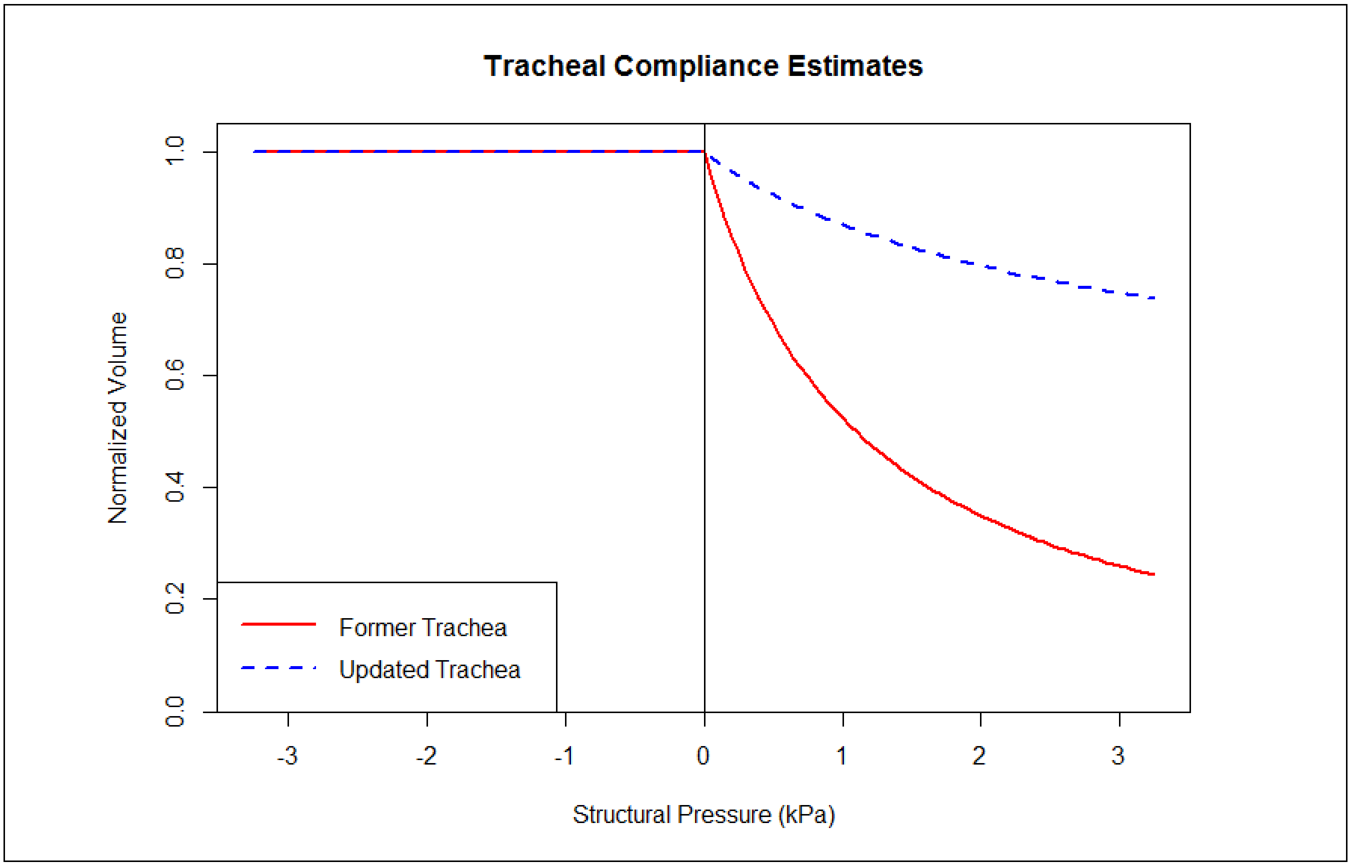

Figure 2. Normalized tracheal volume estimates using the former parameter estimates (red) and the updated parameter estimates (blue).

Pulmonary shunt parameters

Previously published pressure-shunt data collected from 2 California sea lions (Kooyman and Sinnett, 1982) was fit to the following pulmonary shunt equation:

$$\text{Shunt} = 1\text{-}(a\cdot(DV_A\cdot V_A^{-1})^{-b}) \qquad (3)$$

where a and b are fitting parameters, where DV_A is the estimated alveolar volume at depth and V_A is the maximum alveolar volume (Fahlman et al., 2009). Parameters were estimated using a nonlinear least squares model, where a and b were fixed factors. Using this model, the best estimates for the tracheal compliance parameters were 1.061 and 0.166, compared to the previously-used estimates of -1.072 and 0.210 (Fig. 2).

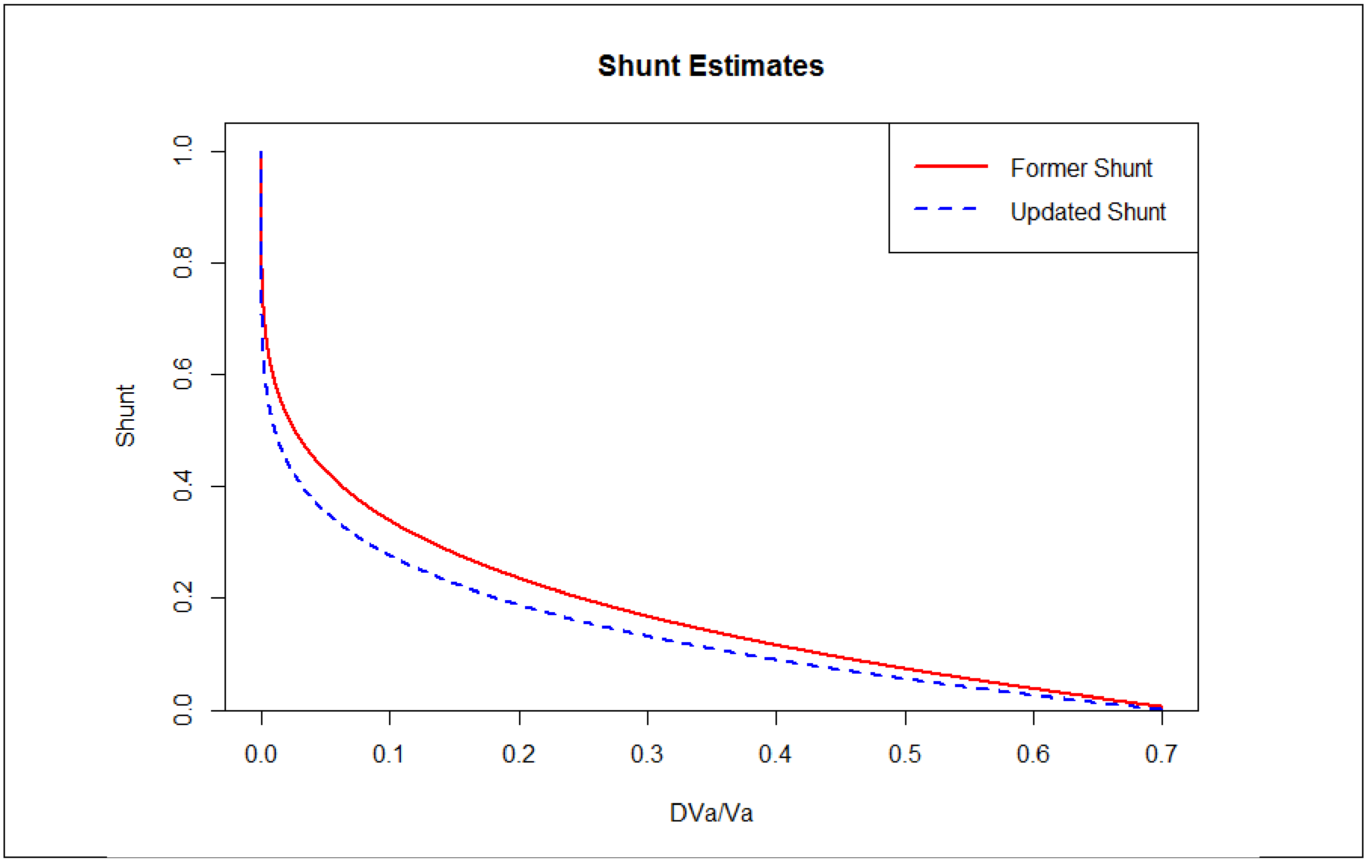

Figure 3. Shunt estimates using the former parameter estimates (red) and the updated parameter estimates (blue).

Aim 2:
Dive data, and concurrent venous and arterial PO2 measurements, for California sea lions have been acquired from Drs. Paul Ponganis and Gitte McDonald and are being used to compare estimated and observed blood PO2 levels during diving. An initial comparison of the observed blood PO2 levels and the estimated values obtained using the updated parameters has been completed.

RESULTS

Aim 1:
Model P_{N_2} Output
Using a dive data set provided by Drs. Paul Ponganis and Gitte McDonald, the model output using the updated parameter estimates has drastically lower nitrogen tensions than the model output using the former parameter estimates in both fast-loading tissues (e.g., muscle, Fig. 4) and slow-loading tissues (e.g., fat, Fig. 5).

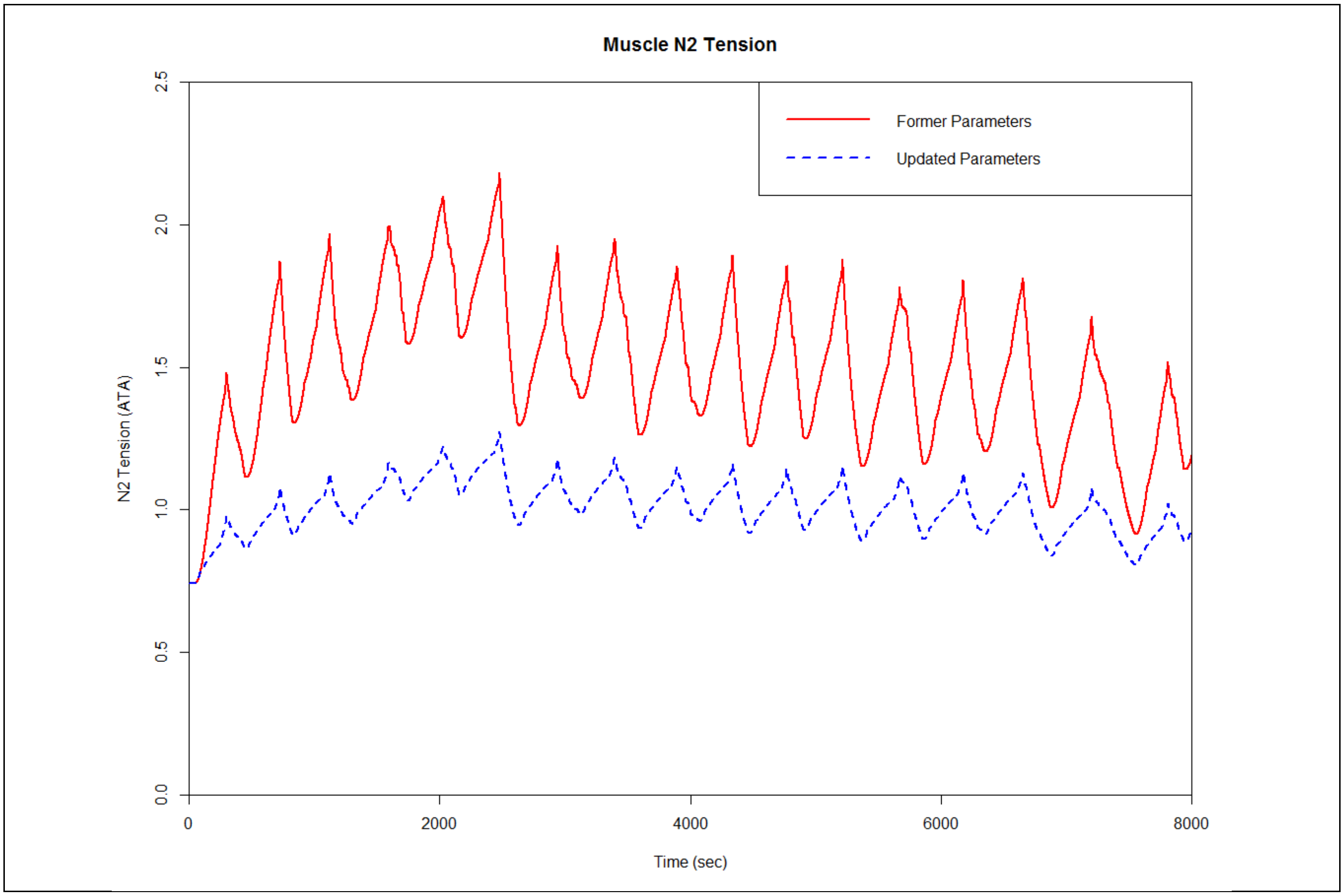

Figure 4. Muscle (a fast-loading tissue) P_{N_2} estimates using the former parameter estimates (red) and the updated parameter estimates (blue) using an actual dive profile from a California sea lion.

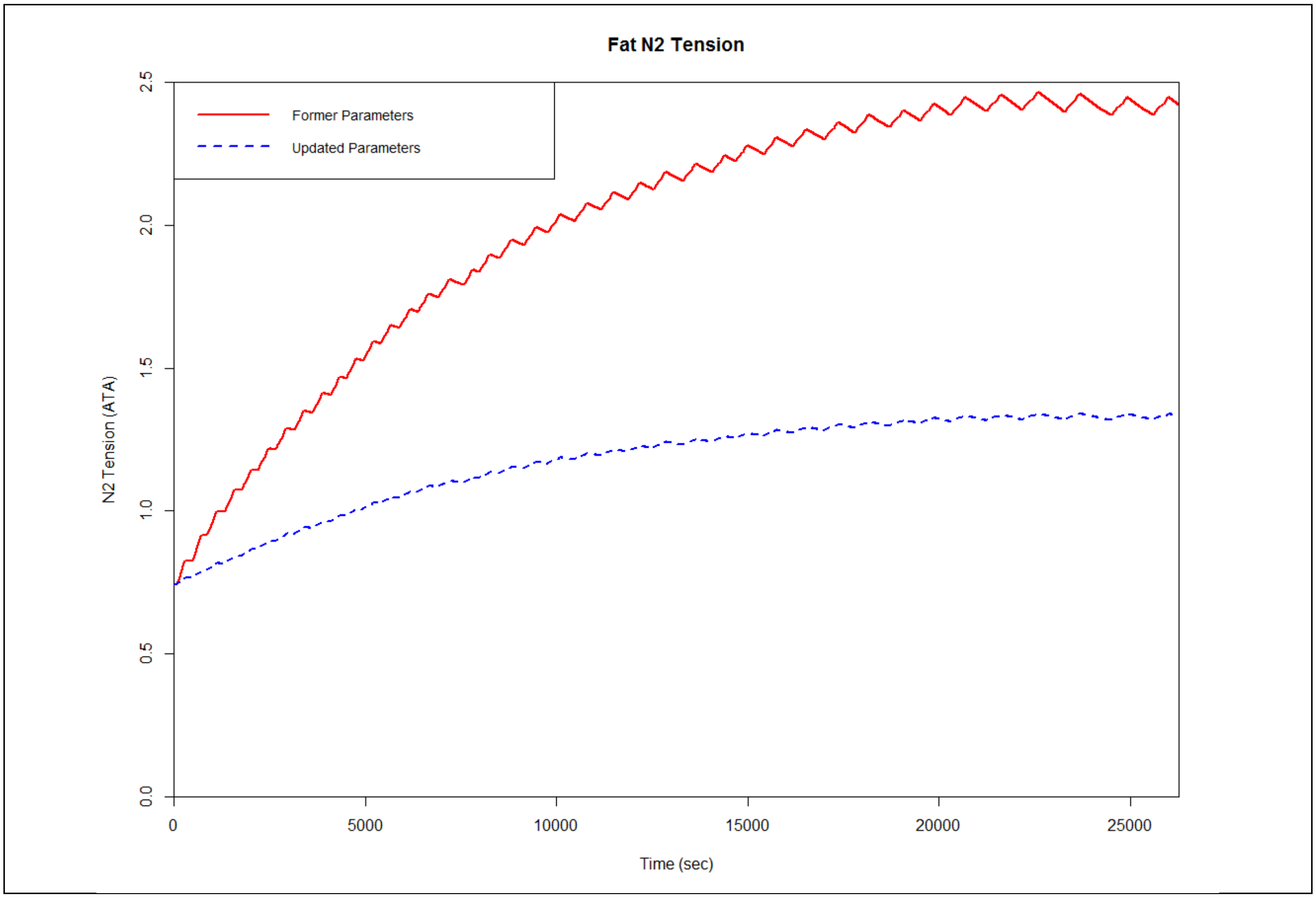

Figure 5. Fat (a slow-loading tissue) P_{N_2} estimates using the former parameter estimates (red) and the updated parameter estimates (blue) using an actual dive profile from a California sea lion.

Model P_{O_2} Output

Using the same dive data set provided by Drs. Paul Ponganis and Gitte McDonald, the model output using the updated parameter estimates has similar oxygen tension estmates to the model output using the former parameter estimates in both fast-loading tissues (e.g., muscle, Fig. 6) and slow-loading tissues (e.g., fat, Fig. 7).

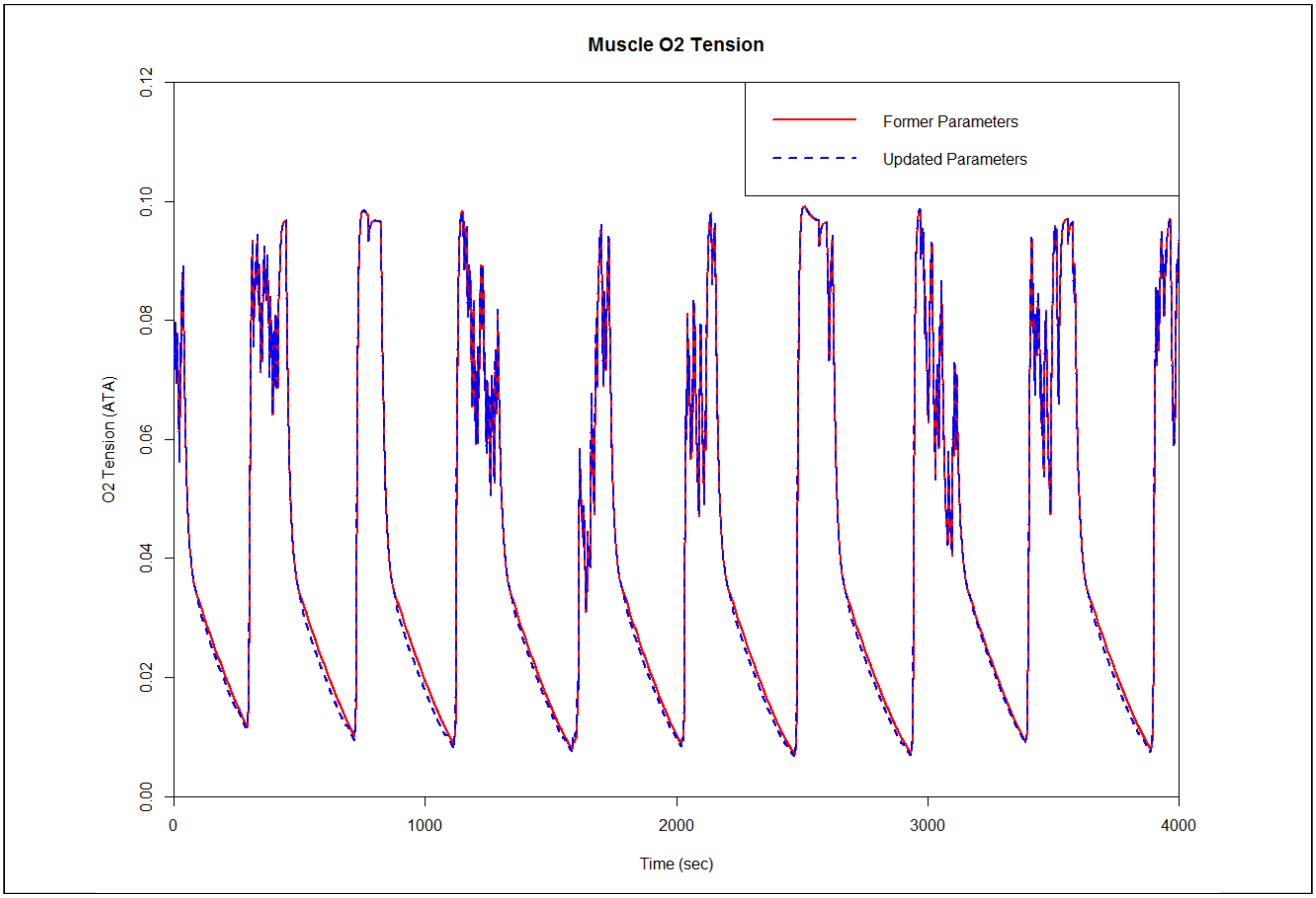

Figure 6. Muscle (a fast-loading tissue) P_{O_2} estimates using the former parameter estimates (red) and the updated parameter estimates (blue) using an actual dive profile from a California sea lion.

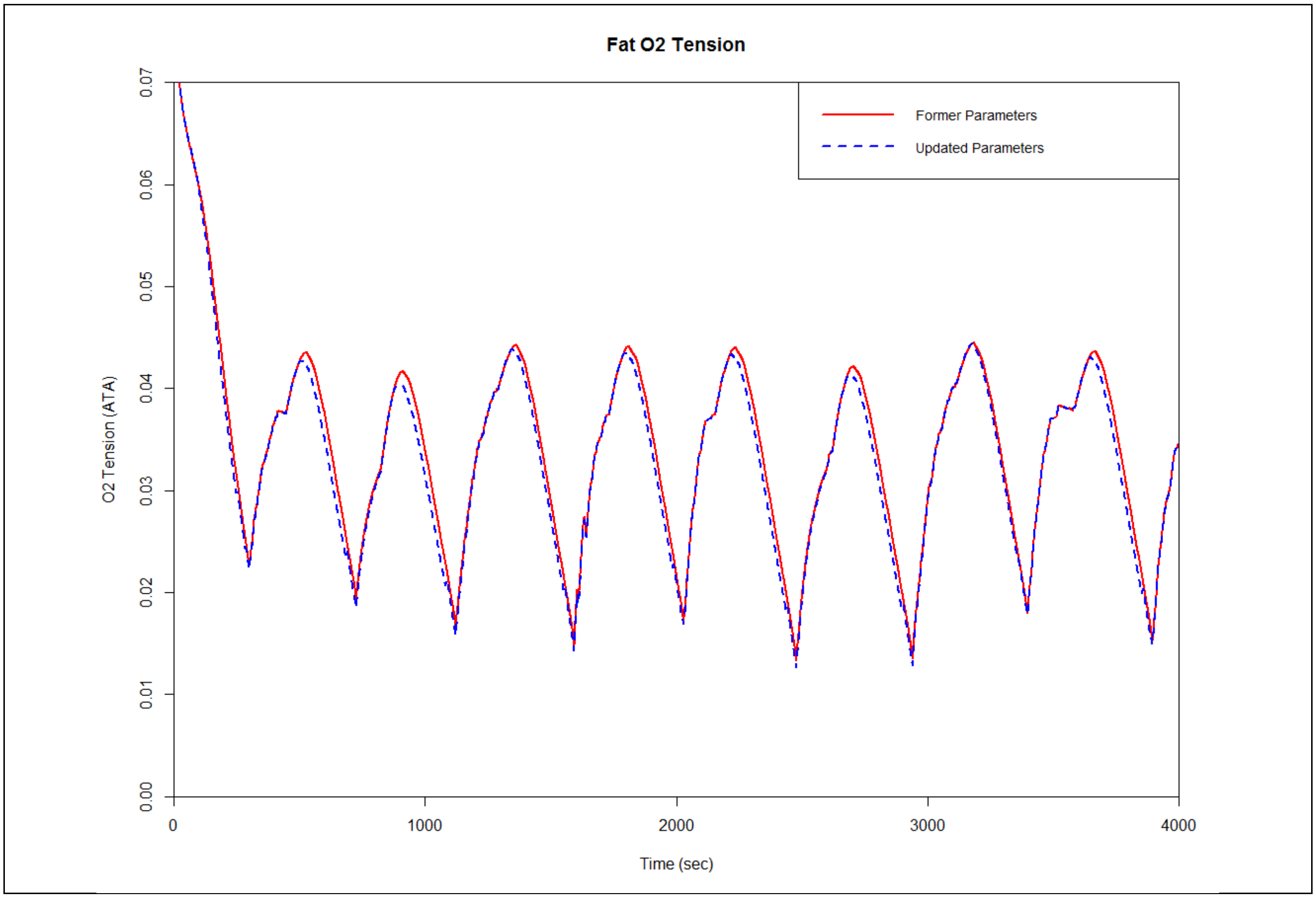

Figure 7. Fat (a slow-loading tissue) P_{N_2} estimates using the former parameter estimates (red) and the updated parameter estimates (blue) using an actual dive profile from a California sea lion.

Aim 2:

An initial analysis of the venous P_{O_2} estimates from the updated model show that they differ slightly from the empirically collected venous P_{O_2} values (Fig. 8).

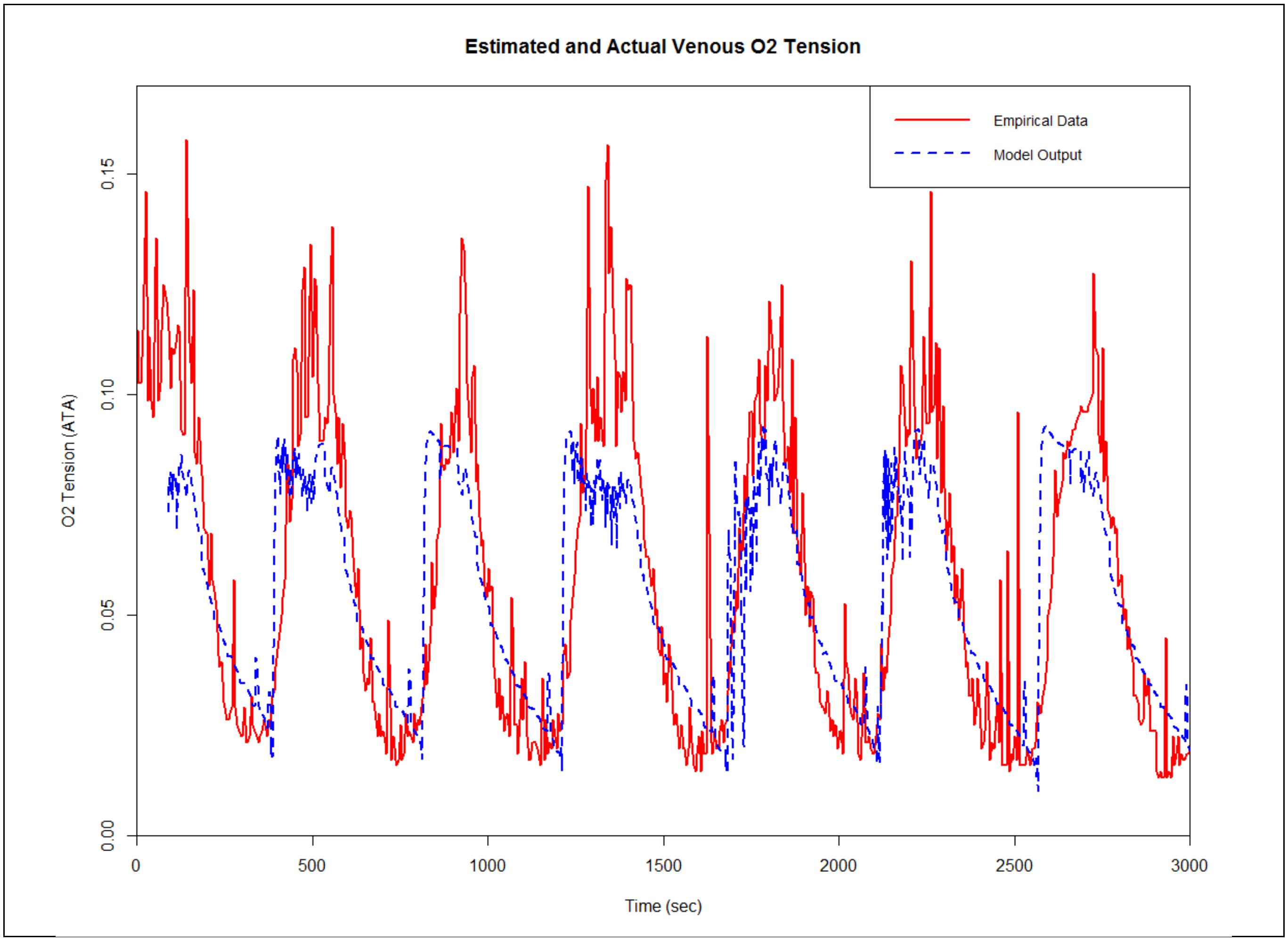

Figure 8. Venous P_{N_2} values from collected empirical data (red) and model estimated output (blue) using a dive profile from a California sea lion.

IMPACT/APPLICATIONS

This work is intended to increase our understanding of the gas tensions in tissues of diving marine mammals. Empirical data is difficult to collect in diving marine mammals and is non-existent for many species. Therefore, modeling is currently a useful tool in estimating gas dynamics in individuals during a dive. Due to recent studies conducted on California sea lions, it is now possible to update a currently used model with species-specific parameter estimates instead of using parameter estimates collected from a variety of species. Since arterial and venous P_{O_2} values are also available for California sea lions, the model output can now be compared to actual values found in a live, diving individual, which allows the model to be calibrated in order to provide the most accurate gas tensions currently available for any individual species.

Results from the completed study will help to improve our understanding of the physiology of marine mammals and estimating inert gas levels in breath-hold divers. The results can be used to determine how changes in dive behavior, in response to anthpropgenic noise as well as changes in prey distribution, affect P_{N_2} in both blood and tissue. Therefore, our results will enhance the fundamental

understanding, interpretation, and mitigation of the effect of anthropogenic sound and climate change, and enable knowledgeable decisions about sonar deployment, related training exercises, commercial and military ship manuevering, and responses to NGO concerns. This should be of value to the US Navy Marine Mammal Program.

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